

NTUTH-96-03

March 1996

Prospect for Heavy Quarks Lighter than M_W at Tevatron and LEP II ¹

George Wei-Shu HOU

Department of Physics, National Taiwan University,
Taipei, Taiwan 10764, R.O.C.

Abstract

As the excitement surrounding the heavy top quark discovery subsides, while the expectation for LEP II physics gathers, it is a good time to sit back and reflect on whether energy regions available to us have been fully explored. We emphasize that a loophole exists where heavy quarks, perhaps the actual top quark itself, could still be hidden below M_W . This would typically involve scalar induced decays of the heavy quark, and could be realized in models with more than one Higgs doublet, e.g. MSSM. We illustrate such mechanisms with two Higgs doublet models, the addition of singlet quarks, as well as reconsidering a fourth family of quarks and leptons. Curiously, the present R_b - R_c problem may be a harbinger of such scenarios. Given that LEP-II would be running soon, and in view of the large amount of data that the Tevatron has collected, we urge our experimental colleagues to conduct a critical analysis.

¹ Talk presented at the JINR-ROC Symposium, June 26 – 28, 1995, Dubna, Russia.

1 Present Data and the Flavor Problem

All experimental data seem to be fully consistent with the Standard Model with 3 fermion generations (SM3). It is truly remarkable that SM3 could account for a very wide range of data. Not only LEP precision tests fail to reveal new effects (except R_b-R_c , see below), the flavor related parameters such as $m_t \cong 180$ GeV and $V_{cb} \simeq 0.8\lambda^2$, $V_{ub} \simeq 1.3\lambda^4 e^{-i\delta}$ ($\lambda \equiv V_{us}$ and δ is the CP violating phase in SM3) could numerically account for subtle effects such as Δm_K , Δm_B , ε_K , ε'/ε and $b \rightarrow s\gamma$.

Remarkable as it is, we should recognize that, “accounting” is one thing, but a deeper “understanding” (*e.g.* gauge invariance as a dynamical principle) of all this is still lacking. To gain some perspective on the parameters of SM3, note that

gauge:	g_1, g_2, g_3	$(\Rightarrow \text{unification?})$
symm. breaking:	$v, \boxed{m_H}$	$\Rightarrow \text{LHC!}$
Flavor:	m_e, m_μ, m_τ	
	$m_u, m_c, \boxed{m_t}$	$\Leftarrow \text{1994-95 Tevatron}$
	m_d, m_s, m_b	
	$s_1, s_2, s_3, \boxed{\delta}$	$\Rightarrow \text{B Factory}$

In all, 13 out of 18 parameters are in Flavor Sector. Furthermore, this number could easily multiply if more fermions are discovered. If gauge couplings g_i are basically understood, while symmetry breaking is partially understood, in comparison, FLAVOR is NOT UNDERSTOOD! This constitutes the Flavor Problem. Many questions are contained here:

- Why 3?
- Why mass and mixing hierarchies?
- Why $m_t \gg m_b$?
- For weak bosons and the top quark, $M_W, M_Z, M_H, m_t \sim v$. This appears to be natural since it is “normal” to expect particles to have mass of order the dynamical scale (*e.g.* hadrons in QCD). The mystery is then, why all fermions (except the top) behave as $m_f \ll v$? They appear more like zero modes at the weak scale (see Fig. 1).

Together with our limited understanding of symmetry breaking, the last point suggest that one could well have more states around the weak scale v . These could be the 4th generation (SM4) fermions, extra Higgs bosons, or the appearance of exotic (nonsequential) fermions.

What do we know about them? Perhaps the discovery of new particles at the v scale may provide us with better understanding of the Flavor Problem.

It is useful to remind ourselves the hard facts at hand:

- A heavy quark weighing 180 GeV has been found during 1994-95 [1]. However, *it is not yet proven to be the top*, since most heavy quark decay scenarios contain b final states. It could well be the 4th generation b' or t' quark, or some exotic quark.
- If a 4th generation exists (call it E, N), then $m_E, m_N > M_Z/2$.
- By same token, there is a firm lower bound of $M_Z/2$ for $m_t, m_{b'}$ and $m_{t'}$.

In contrast, the limit of $m_t > 62$ GeV from “ Γ_W ” measurement by CDF is not firm since it assumes $V_{tb} = 1$. The 1989-91 limit of $m_t > 91$ GeV by CDF and 1994 limit of $m_t > 130$ GeV by D0 are not firm because the SM3 value of $\text{BR}(t \rightarrow \ell\nu + X) \simeq 1/9$ is assumed.

Our theme, therefore, is that heavy quarks (t, b', t' or exotics) COULD lurk/hide below M_W IF hadronic decays predominate the decay rate [2]. The existence of a heavy quark Q' with $m_{Q'} < M_W$, together with the observed heavy quark Q with $m_Q \simeq 175$ GeV, imply that there would be a lot of fun ahead of us at both the Tevatron and LEP II.

2 Mechanism to hide Top below M_W

As an illustration of how the Tevatron experiments could have missed heavy quarks with $m_Q < M_W$, let us discuss the case for a “light” top quark [2]. We define the top quark as the doublet partner of the b quark. For $m_t < M_W$, the SM3 decay chain is $t \rightarrow bW^* \rightarrow bf\bar{f}'$, where W^* is virtual (see Fig. 2). This process is suppressed by a propagator and coupling factor $g^4/(q^2 - M_W^2)^2$ (i.e. still “remembering” 4-Fermi interaction) as well as 3-body phase space. If some boson X exist and couples to t - q quarks with strength λ_{tqX} , then, if $m_X < m_t$, this induces a 2-body decay. If λ_{tqX} is not too small compared to g (the weak gauge coupling), and if $X \rightarrow \text{hadrons}$ (on-shell X decay), then top decay could be dominated by hadronic final states due to X production, and it would be difficult for CDF/D0 to tell from multijet background. Note that this cannot occur in SM3, since tcH coupling does not exist. However, X could be exotic scalars such as H^+ or h^0 . These could arise from minimal SUSY (MSSM), where the scalars could also be the top squark \tilde{t} while q above becomes the chargino χ^+ or neutralino χ^0 . The simplest construction, however, would be the addition of an extra

scalar doublet. In the following, we shall mainly use two Higgs doublet models (2HDM) as a means of illustration, before turning to more elaborate models. For sake of space, we touch on salient features without giving any detail.

3 Two Higgs Doublet Models

The “standard” 2HDMs invoke the natural flavor conservation condition (NFC) of Glashow and Weinberg, where each type of fermion charge receive mass from one Higgs doublet only. The mass and Yukawa matrices are then simultaneously diagonalized, and FCNC couplings of neutral scalars are absent by construction. For Model I, both u and d quarks receive mass from the same doublet, while for Model II, they receive mass from different doublets. The latter is popular because it naturally arises in MSSM, and has been rather well studied.

It is possible to foresake the NFC condition by assuming some approximate (global) flavor symmetry in the Yukawa couplings to protect from low energy FCNC constraints. This was noted already some time ago [3], and has been discussed widely recently.

Let us see how a light top could be hidden in these models.

3.1 Model I: $t \rightarrow bH^+$

In this model, the H^+ coupling is

$$\frac{\sqrt{2}}{v} V_{tb} \bar{t} (\cot \beta m_t L + \cot \beta m_b R) b + h.c., \quad (1)$$

where the parameter $\cot \beta = v_2/v_1$ is mainly constrained by Δm_K and Δm_B . The coupling could evade the stringent $b \rightarrow s\gamma$ constraint by a cancellation mechanism between H^+ and W^+ effects [4]. It evades direct CDF search for $t \rightarrow bH^+$ as follows. CDF finds [5] that if $H^+ \rightarrow \tau^+\nu$ is close to 100%, the entire region of $m_{H^+} < m_t < M_W$ is ruled out. However, if it falls below 50%, then the entire region becomes allowed! In Model I, since

$$\Gamma(H^+ \rightarrow \tau^+\nu)/\Gamma(H^+ \rightarrow c\bar{s}) \simeq 1/N_C = 1/3, \quad (2)$$

one has $\text{BR}(H^+ \rightarrow \tau^+\nu) \leq 30\%$. What is the tbH^+ coupling strength? One sees from eq. (1) that $\lambda_{tbH^+} = V_{tb} \cot \beta \lambda_t$. From $b \rightarrow s\gamma$ one infers that $\cot \beta < 2$, while $0.25 < \lambda_t < 0.5$ for this mass range. We thus find [2] that $\lambda_{tbH^+} \sim 0.5 - 1 \sim g$, hence, $t \rightarrow bH^+ \gg t \rightarrow bW^*$ in the mass range of $m_{H^+} < m_t < M_W$.

3.2 Model II: $t \rightarrow bH^+$ (thought to be ruled out)

In this case one replaces $\cot \beta$ by $-\tan \beta$ in the coefficient of the m_b term. This makes all the difference compared to Model I. The H^+ contribution now adds constructively to the W boson contribution (as well as the large QCD correction term that arises at leading log (LL) order). What is interesting [4] is the appearance of a $\tan \beta$ -*independent* term that contributes for any $\tan \beta$ value. This amounts to a strong enhancement effect that is always there, leading to a stringent constraint from the observation of $b \rightarrow s\gamma$ and $B \rightarrow K^*\gamma$ by CLEO. The upshot, as stated by CLEO [6], is that $m_{H^+} > 300$ GeV.

At LL order, one has significant scale dependence, which is supposedly resolved at next-to-leading (NLL) order. Such a calculation is rather tedious and intricate. A partial calculation suggests that new cancellation effects emerge at NLL order. The details cannot be presented here [7], but depending on the sign of new NLL terms, it may be possible to evade $b \rightarrow s\gamma$ bound for $m_t < M_W$ and $0.6 < \tan \beta < 1$. At the same time, the right hand side of eq. (2) gets multiplied by $m_\tau^2/(m_s^2 + \cot^4 \beta m_c^2)$. Thus, one needs $\tan \beta < 1$ to evade CDF direct search for $t \rightarrow bH^+$. The upshot, then, is that $m_H^+ < m_t < M_W$ is in fact possible if $\tan \beta \sim 1$, which is a value where the distinction between Model I and II are blurred.

3.3 General 2HDM: $t \rightarrow ch^0$

Without NFC condition, in general one has FCNC neutral Higgs boson couplings at tree level. However, Nature seems to have “naturally” implemented some approximate flavor symmetry, which is reflected in the mass and mixing hierarchies. This suggests [3] that low energy FCNC constraints could still be effectively evaded, *without* constraining the high energy behavior. The basic observation here then is that [8], there is in fact almost no *direct* constraint that forbids FCNC t - c -scalar couplings. It is NOT against any principle or experimental result [9]. Assuming that some FCNC neutral scalar h^0 is rather light, but still decaying via $b\bar{b}$, then $t \rightarrow ch^0$ (followed by $h^0 \rightarrow b\bar{b}$) decay provides a somewhat exotic but otherwise perfectly possible scenario where $m_t < M_W$ could be realized [2].

4 Singlet Charge 2/3 Quark and $R_b - R_c$ Problem

Another way to induce FCNC is to break GIM mechanism. The easiest way beyond SM3 is the addition of left-right singlet charge 2/3 quarks Q_L and Q_R , which affects top physics via

t - Q mixing. One can show [10] that physical m_u and m_c eigenvalues could remain small even with large u - Q and c - Q mixings. Since tcH coupling is induced by the presence of *both* c - Q and t - Q mixings, to allow $t \rightarrow cH$ decay to dominate over $t \rightarrow W^*$ one needs both mixings to be very large. However, on closer inspection, one would find that too large a c - Q mixing would lead to too small a Zcc coupling. Interestingly, it has recently been reported that the Zcc coupling is 2.5σ below SM3 expectations, while Zbb coupling seems to be almost 4σ above. Taking these experimental indications as hints, it is possible to construct [11] a solution to the so-called $R_b - R_c$ problem (the only seeming discrepancy with SM3 in town) in this context, at the price of introducing a second Higgs doublet. The latter provides for additional weak doublet splitting (ΔT) via $m_{H^+} > v \gg m_{h^0}$, while the exotic neutral Higgs h^0 should be as light as possible to allow maximal phase space for facilitating the hiding of the actual top quark below M_W . The dominantly singlet quark Q emerges as the heavy quark observed at the Tevatron. It still dominantly decays via bW mode, but also decays via sW , cZ , tZ , ch^0 , th^0 , with many interesting consequences [11].

The scenario bears some similarity with, but is also distinct from, the MSSM solutions to the R_b (but not R_c) problem, where one demands light “stop” and chargino/neutralinos.

5 Fourth Generation Scenarios

Some recent work illustrates that a fourth generation could be entertained from a high scale perspective. Elaborate studies have been conducted with SUSY GUT inspired structures. For example, the work of Gunion, McKay and Pois [12] takes top (partner of b) to be the quark discovered at Tevatron. They then demonstrate that it is possible to have $m_{b'} < m_{t'} < 120$ GeV, where both heavy quarks remain unobserved if $t' \rightarrow b'W^*$, where W^* decay is rather soft, while b' decays via loop induced $b' \rightarrow bH$ mode [13]. The discussion is rather elaborate, but the point, to some extent, is to allow for a fourth generation but also at the price of additional “light” new particles, which are again charged or neutral scalar bosons. In a similar framework, the work of Carena, Haber and Wagner [14] suggests that $m_t \cong M_W$ via neutralino induced decays $t \rightarrow \tilde{t}\chi^0$ (while $\tilde{t} \rightarrow c\chi^0$). The fourth generation t' quark decays via standard bW channel and is the one observed at Tevatron. One again has light new particles below M_W .

It may be worthwhile to strip ourselves from high scale prejudices and reassess the issue of possible physics of a fourth generation at Tevatron and LEP II.

6 Conclusion

We have seen many scenarios where one may have particles below the W scale. In all cases one needs some light scalar particle to facilitate their hiding. We conclude that “light” heavy quarks, below M_W , or at least below m_t , is quite an open topic for experimental study.

Acknowledgement. This work is supported in part by grant NSC 85-2112-M-002-011 of the Republic of China. I wish to thank G. Bhattacharyya, G. C. Branco, C. Q. Geng, H. C. Huang, E. B. Tsai and P. Turcotte for collaborative work.

References

- [1] See M.J. Wang’s contribution, this proceedings.
- [2] W.S. Hou, Phys. Rev. Lett. **72**, 3945 (1994).
- [3] T.P. Cheng and M. Sher, Phys. Rev. D **35**, 3484 (1987).
- [4] W.S. Hou and R.S. Willey, Phys. Lett. **202B** (1988) 591.
- [5] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **72**, 1977 (1994).
- [6] M.S. Alam *et al.* (CLEO Collaboration), Phys. Rev. Lett. **74**, 2885 (1995).
- [7] See W.S. Hou *et al.*, Prog. Theor. Phys. **94**, 1089 (1995); and references therein.
- [8] W.S. Hou, Phys. Lett. B **296**, 179 (1992).
- [9] L. Hall and S. Weinberg, Phys. Rev. D **48**, R979 (1993).
- [10] W.S. Hou and H.C. Huang, Phys. Rev. D **51**, 5285 (1995).
- [11] See G. Bhattacharyya, G.C. Branco and W.S. Hou, CERN-TH/95–326 (hep-ph/9512239), to appear in Phys. Rev. D; and references therein.
- [12] J.F. Gunion, D.W. McKay and H. Pois, Phys. Lett. B **334**, 339 (1994); Phys. Rev. D **53**, 1616 (1996).
- [13] W.S. Hou and R.G. Stuart, Phys. Rev. Lett. **62**, 617 (1989); B. Haeri, A. Soni and G. Eilam, *ibid.*, 719 (1989).

[14] M. Carena, H.E. Haber and C.E.M. Wagner, CERN-TH/95-311 (hep-ph/9512446).

Figures

Fig. 1. Illustration of mass scales. The “usual” quarks and leptons appear as “zero modes”, while W , Z , H and the top quark appear as “normal” states on the v scale, suggesting the existence of many more such particles.

Fig. 2. Feynman diagrams to illustrate mechanism for hiding top quark below M_W .

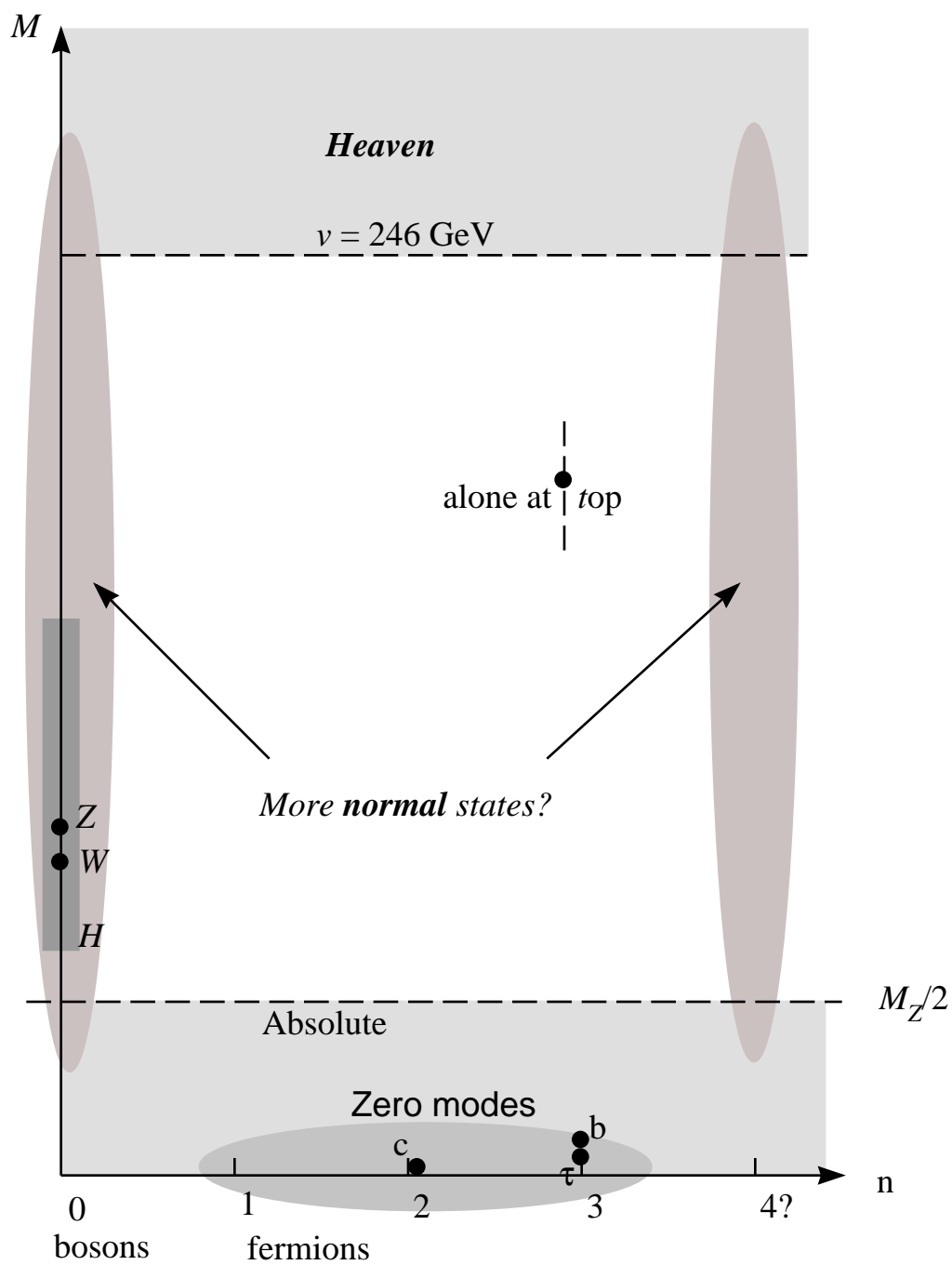


Fig. 1

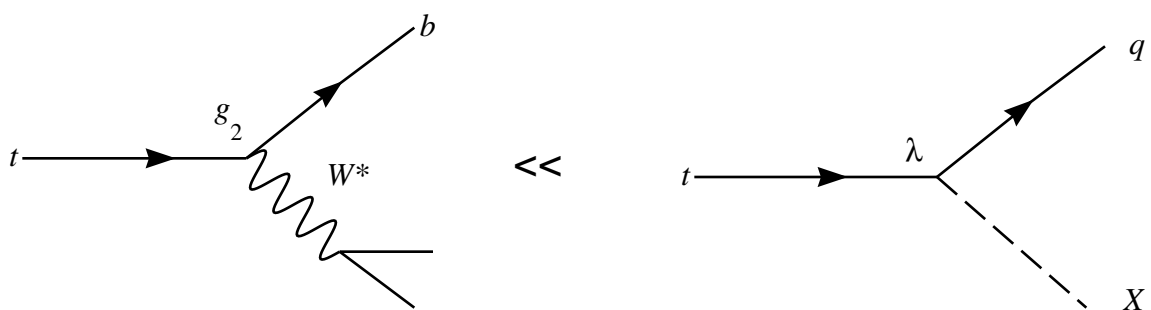


Fig. 2